Rapid Assessment of Current Velocities in the Coastal Ocean

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Abstract

The circulation off the mouth of a coastal plain estuary, the Chesapeake Bay, was assessed under conditions of weak freshwater discharge. Current velocity observations obtained with an acoustic Doppler current profiler during 25 hours in September 1995 were separated into tidal and subtidal contributions. The subtidal flow was dominated by wind forcing. The tidal flow was presented as ellipses that illustrated the preferred orientation of this flow, which was influenced by the coastal morphology.

1. Introduction

The rapid assessment of coastal current velocities in a given area has important implications for environmental and military applications. The present study illustrates one example of describing the coastal circulation in a region influenced by buoyant discharges. The region of the Chesapeake Bay outflow is used as a test case. The Chesapeake Bay is located on the eastern coast of the United States and is the largest estuary of the country. Its plume is derived from a mean annual discharge of approximately 2000 m^3/s. The hydrography of the plume has been described in several studies [1], [2], [3] that show the importance of wind forcing on the fate of the buoyant discharges. The plume spreads offshore with southwesterly winds and remains close to the mouth of the estuary and to the coastline with northeasterly winds. The circulation associated with this plume, however, has not yet been described in detail. This paper begins to address this issue.

The overall objective of this study is to rapidly assess the coastal circulation off the mouth of an estuary under weak river discharge conditions, and in particular, to determine the influence of wind forcing on that coastal circulation. In order to accomplish this objective, an acoustic Doppler current profiler (ADCP) was towed for 25 hours between September 25 and 26, 1995 off the mouth of the Chesapeake Bay along the track shown in Figure 1. This rapid sampling of the area allowed the assessment of the coastal circulation within a period of 30 hours after the experiment started.

2. Data Collection

The survey was carried out during the time of the year of weakest discharge and in the driest year of the decade. The mean river discharge into Chesapeake Bay in September 1995 was less than 500 m^3/s, considerably less than the climatological mean of 1000 m^3/s for that month. The survey also took place under the influence of northerly winds, and after a period of relatively strong (~0.1 Pa) northeasterly winds as recorded at the Chesapeake Light Tower and at the Chesapeake Bay Bridge Tunnel by the U.S. National Oceanic and Atmospheric Administration (NOAA).

The current velocity data were obtained with a 600 kHz broadband ADCP manufactured by RD Instruments. The instrument was mounted on a catamaran and towed from the NOAA *R/V Ferrel*. The vertical resolution (or bin size) of the velocity measurements was 0.5 m so that the first usable bin was centered at approximately 2.25 m. The velocity data were collected in ensembles of 30 s, which gave a horizontal resolution of 75 m towing at a speed of ~2.5 m/s . The collection of ADCP data was combined with conductivity-temperature-depth (CTD) profiles obtained every 2 nautical miles along the ship track to characterize the potential influence of freshwater in the area. Navigation was performed with the aid of differential Global positioning system (DGPS). The grid over which the survey took place was approximately 60 km in the along-shelf direction from Cape Charles, Virginia, to False Cape, at the border between Virginia and North Carolina, and 20 km in the cross-shelf direction.

3. Data Description

3.1. Instantaneous Data

Given the river discharge and wind forcing conditions prevailing at the time of this survey, a very weak plume was observed off the mouth of the Chesapeake Bay. The salinity difference between plume and ambient waters was around 2 as indicated by instantaneous measurements (Fig. 1a). This weak salinity difference is quite contrasting to the salinity difference of September of 1996 when it was more than 10. Therefore, the buoyancy forcing was very weak and probably had a minor influence on the coastal circulation in the area at the time of the study. This idea is explored later by assessing the importance of wind forcing on the coastal circulation.

The instantaneous measurements of near-surface flow and salinity (Fig. 1a) showed spatial distributions that are typical of a plume influenced by downwelling winds as characterized in the modeling studies of [4] and [5]. These typical characteristics are: a region where the plume turns anticyclonically, the turning region; a transition region where the flow converges between the turning region and the coastal current as seen by the speed decrease in the alongshore flow south of the mouth of the bay; and the formation of a coastal current. Also, the freshest water remains constrained to a very narrow band, narrower than the internal radius of deformation of around 7 km, along the coast. These instantaneous measurements are, however, tidally aliased, *i.e.*, they are biased by the different stages of the tidal cycle over which the observations were made. Then, in order to obtain a synoptic picture of the flow field, the influence of the tides on the instantaneous flow must be distinguished from the subtidal (or mean) current.

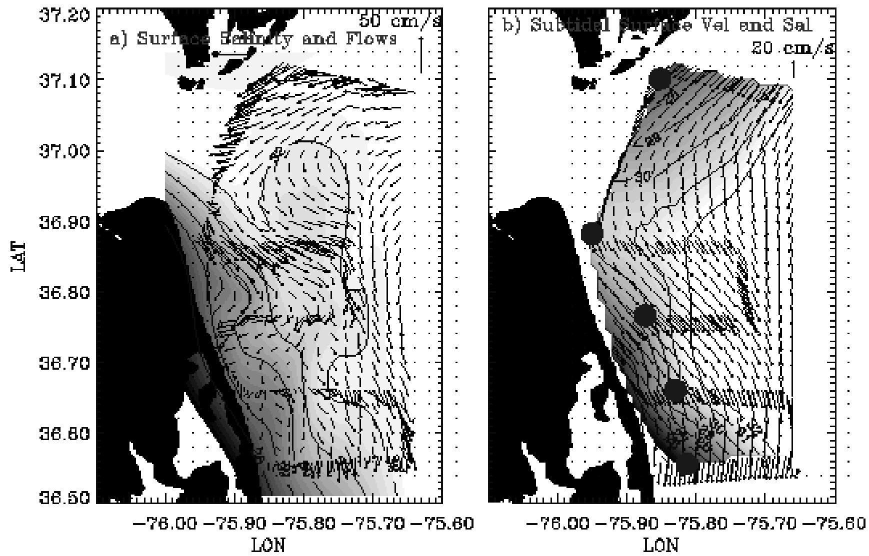

Figure 1. Study area off the mouth of the Chesapeake Bay. (a) Instantaneous observations of near-surface flow (vectors) and salinity (shaded contours). (b) Subtidal near-surface flow and salinity. The ship track is denoted by the closely spaced vectors. The gridded vectors are generated from interpolation. The location of the l nodes at which the least squares fit is performed is denoted by the filled circles in (b).

3.2. Fitting Technique

In order to separate the tidal signal from the instantaneous measurements, a least-squares technique was used. This technique has been used by [6] and assumes that each component of the current velocity observed $u_{io}(x,y,t)$, where the subscript i denotes one component, has a contribution from a subtidal current u_{im} plus one from a lunar semidiurnal (period of 12.42 h) tidal current, *i.e.*,

$$u_{io}(x,y,t) = u_{im}(x,y) + a_i(x,y)\cos(\omega_{M2}\, t) + b_i(x,y)\sin(\omega_{M2}\, t), \qquad (1)$$

where ω_{M2} is the frequency of the lunar semidiurnal tidal component ($2\pi/12.42$ h). The subtidal flow component (or could also salinity), and the functions $a_i(x,y)$ and $b_i(x,y)$, are given by:

$$u_{im}(x,y) = \Sigma_l\, \alpha_l(x,y)\, \phi_l(x,y),$$
$$a_i(x,y) = \Sigma_l\, \beta_l(x,y)\, \phi_l(x,y),$$
$$b_i(x,y) = \Sigma_l\, \gamma_l(x,y)\, \phi_l(x,y).$$

The parameters α_l, β_l, γ_l, are to be found by minimizing the least square error between observations and fit at each of the "l" nodes located at $(x_l\, ,y_l)$. The functions $\phi_l(x,y)$ are base

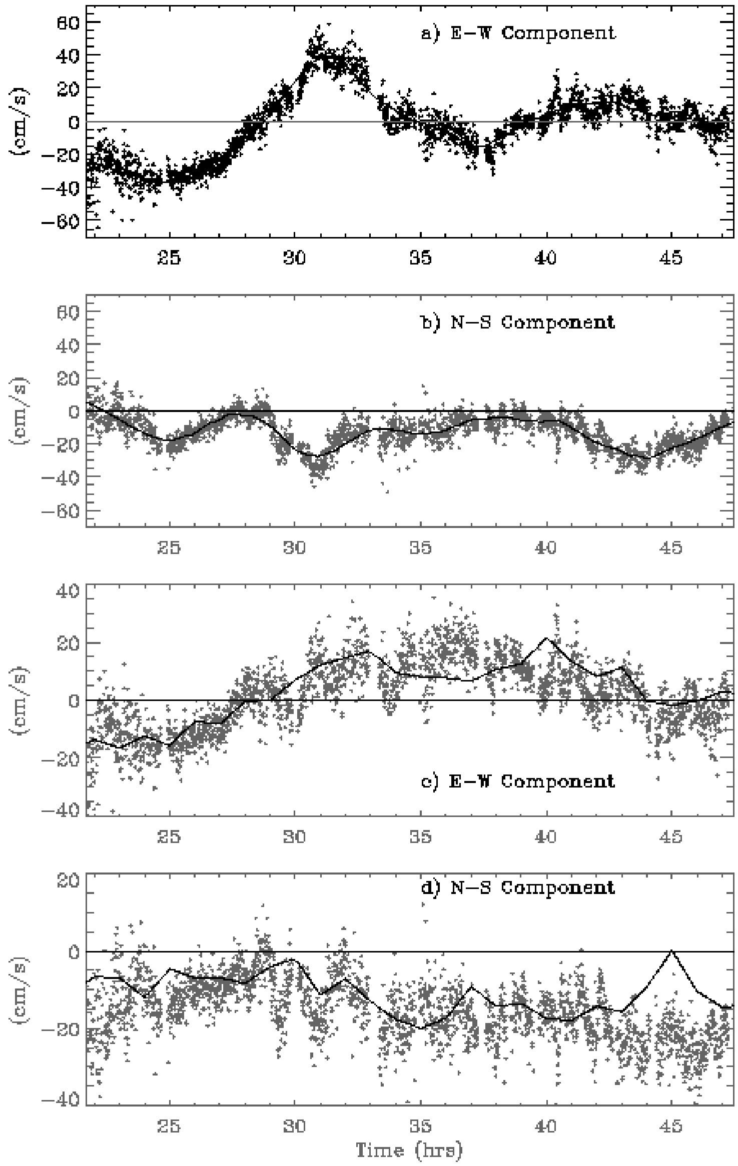

Figure 2. Instantaneous observations, represented by dots, compared to the least squares fit, denoted by continuous lines in (a) and (b). (c) and (d) present the subtidal flow components, as dots, compared to the wind-induced flow (continuous lines) as explained by (3).

functions that have been chosen as biharmonic splines [6], *i.e.*

$$\phi_l(x,y) = \{(x - x_l)^2 + (y - y_l)^2\} \{\ln([(x - x_l)^2 + (y - y_l)^2]^{1/2}) - 1\}. \qquad (2)$$

The least squares fit obtained with equations 1-2 and 5 nodes (Fig. 1b), reproduced the most prominent variations of both components of the observed flow (Fig. 2a, b). The goodness of fitdepends on the position of the nodes, *i.e.*, variations to the node location yield different subtidal and tidal flow fields. The node locations chosen here were optimized in such a way that the noise (difference between observations and fitted values) had zero mean and variance that was a small fraction (less than 10%) of the variance of the observations. In addition, the optimal node locations were chosen for those that reproduced the tidal currents from moored current meters (data not presented here).

3.3. Subtidal Data

The subtidal flow obtained with the technique mentioned above reflects the contribution from wind forcing, from density gradients, and from forcing with periods greater than one tidal cycle (*e.g.* coastal waves). The resulting subtidal flow (Fig. 1b) showed a general tendency for southward flow throughout the domain. As seen later, this was due mostly to the forcing from the predominantly northerly winds. Another feature of the subtidal flow was the southward translation of the turning region of the Chesapeake Bay outflow. This turning region appeared to the south of the Chesapeake Bay mouth due to the interaction between the southward ambient flow and the estuarine outflow as suggested by the numerical results of [7]. The band of low salinity (Fig. 1b) remains very thin and close to the coast as a consequence of the weak buoyancy forcing from the estuary. An interesting question to answer is how much of the subtidal flow obtained from the least squares fit and shown in Figure 1b is due to wind forcing?

In order to assess the influence of wind forcing on the subtidal flow, a complex regression between the wind velocity and the detided velocity was performed. Hourly wind observations were interpolated to 30 s to match the sampling interval of the current velocities. This allowed the complex regression estimate to relate wind forcing to subtidal flow. The relationship between the wind and the subtidal flow was evident (Fig. 2c and 2d). In fact, the wind-induced flow produced a flow pattern that was very similar to the subtidal flow of Figure 1b according to the complex regression that yielded the following equations:

$$
\begin{aligned}
u &= 0.04\ W_x \\
v &= -0.04 + 0.04\ W_y\ . \qquad (3)
\end{aligned}
$$

These relationships explained 90% of the spatial variability of the subtidal flow. In (3), u and v were the east-west and north-south components of the current velocity, respectively, and W_x, W_y were the corresponding components of the wind velocity. This fit indicated that the north-south and the east-west components of the flow were approximately 4% of the north-south and the east-west components of the wind velocity, respectively. The -0.04 on the v component of the flow denoted a residual flow of 0.04 m/s directed to the south when the wind velocity is zero. This was consistent with the typical ambient coastal flow in this area of the Mid-Atlantic Bight [2]. The very high percentage of the subtidal flow variability explained by wind forcing was a consequence of the weak freshwater discharge onto the coastal ocean at the time of the study. This simple relationship between wind velocity and surface velocity allows the rapid assessment of the subtidal near-surface coastal circulation off the Chesapeake Bay only with wind velocity measurements. This assessment will, of course, be restricted to periods of weak freshwater discharge to the coastal ocean.

3.4. Tidal Data

The semidiurnal tidal contribution to the observations was obtained with the second and third terms on the right hand side of (1). The coefficients $a_i(x,y)$ and $b_i(x,y)$ were used to calculate the semidiurnal tidal ellipses following [8]. These ellipses are drawn in Figure 3 over the bathymetry of the study region. The orientation and ellipticity (ratio of the semi-minor axis of the ellipse to the semi-major axis) of the near-surface tidal currents appeared influenced by the coastline morphology. The ellipticity was lowest at the entrance to the Chesapeake Bay as the tidal currents were funneled into and out of the estuary. The ellipticity was greatest to the North and East as reflection of the rotary character of the tidal currents. The orientation of the ellipses suggested, once more, the funneling effect that the bay mouth has on the tidal currents entering and leaving the estuary. This orientation also suggested the influence of coastline morphology on the distribution of tidal currents. This representation of tidal properties was the first high-spatial resolution (less than 5 km) effort to characterize the distribution of the semidiurnal tidal ellipses off the Chesapeake Bay mouth. This is not the definitive distribution of tidal properties in the study area but offers an idea (and rapid assessment) of the spatial patterns that should prevail.

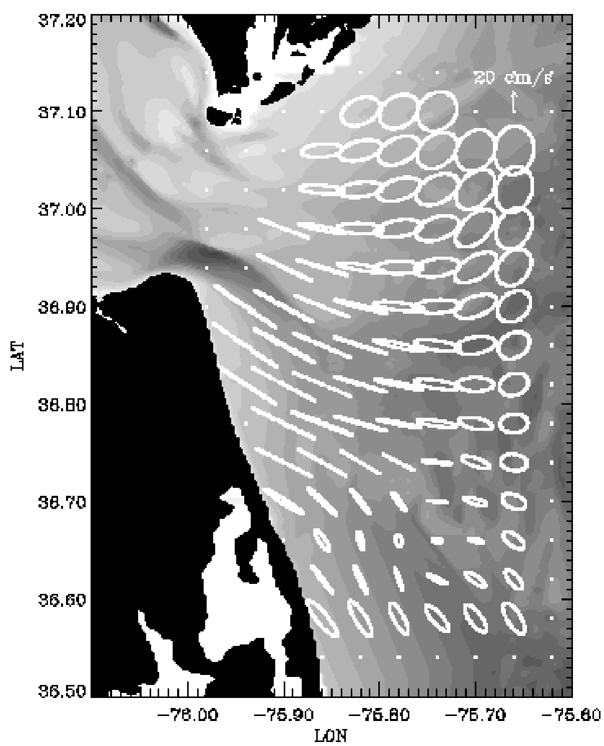

Figure 3. Near-surface semidiurnal tidal ellipses plotted over a regular grid of interpolates from the ship track shown in Figure 1. The bathymetry of the area is shown, for comparison with the orientation and ellipticity of the ellipses, as shaded contours. Deep areas are represented by darker shades.

4. Summary

Current velocity measurements with high spatial resolution were made off the mouth of the Chesapeake Bay in order to rapidly assess the coastal circulation off the mouth of an estuary under weak river discharge conditions. In particular, the influence of wind forcing on the coastal circulation was elucidated. The current velocity measurements were obtained with a towed acoustic Doppler current profiler during 25 hours between September 25 and 26, 1995. Ancillary measurements consisted of water temperature and salinity, and wind velocity. The current velocity measurements contained tidal and subtidal signals that were separated with a least squares technique as in [6]. The least squares fit was very good as it reproduced the salient temporal variations of the instantaneous measurements. The fit yielded a subtidal flow that featured a predominantly southward component and a turning region of the estuarine outflow that was advected southward by the coastal ambient flow. The latter feature agreed with numerical results dealing with a similar problem of an estuarine outflow interacting with an ambient flow [7]. The subtidal flow field was mostly caused by wind forcing as buoyancy forcing was very weak. This subtidal velocity flowed at 4% of the wind velocity. In addition to the wind-induced component, the subtidal flow was influenced by a southward ambient flow of 0.04 m/s.

The least squares fit also identified a semidiurnal tidal flow contribution that showed influence of the coastal morphology on the orientation and ellipticity of the tidal ellipses. These tidal ellipses were more elliptic away from the mouth and became more rectilinear at the constriction of the estuary. The orientation of the ellipses roughly followed the morphology of the coastline. The spatial distribution of these tidal ellipse properties confirmed the expected funneling effect of the Chesapeake Bay entrance on the tidal flows entering and leaving the estuary.

The analysis technique used in this study allows the assessment of the coastal circulation of a region influenced by tidal and other forcings (*e.g.* wind and buoyancy) in approximately 30 hours: 25 hours of measurements and a few hours of data processing and analysis. The advantage of this technique is that it is relatively simple to apply to a data set and produces rapid results. The disadvantage is that it produces results that are statistically reliable but not dynamically reliable because the technique disregards any hydrodynamic aspect of the study area.

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